Course Name: Newtonian Mechanics With Examples
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Week 02
Lecture - 05

Welcome to the second week of this course, Newtonian Mechanics with Examples. In the previous week, we covered a little bit of mathematical preliminaries on scalars, vectors, and tensors. So this week we are going to start with the physics topics proper. So we shall start by reviewing the basic Newton's law of motion. So before going into the subjects I feel that this is a good point to sort of discuss a little bit about the philosophy and the learning objectives of this course. So first thing is that you can expect that there will be lot of examples as the title suggests, and these examples will be taken mostly from our everyday, day-to-day life.

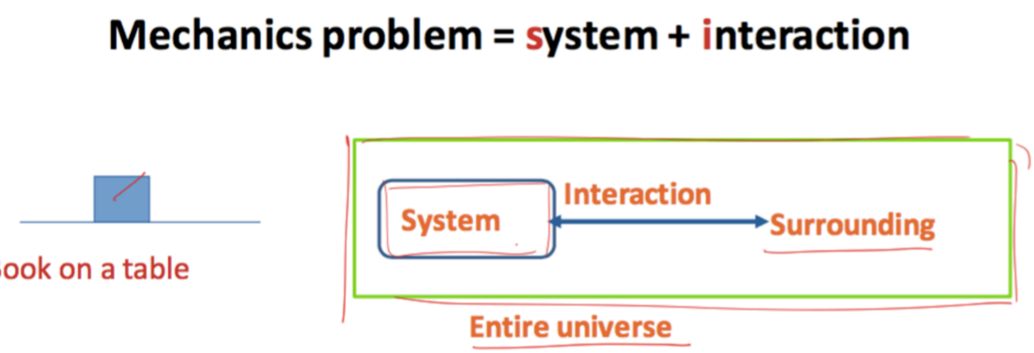
So, the point is that if you want to learn mechanics well, you need to build good physical intuition about real-life experiences. So that being said, I want to make a couple of remarks. First, I assume that all of you have already seen mechanics at the high school level. So I will deliberately try to avoid those examples which are very common in high school text books, such as for example, Pulley.

So the emphasis will be on the real-life part, so the text book examples that you have seen are somewhat ideal. So they ignore a lot of crucial aspects. So we will include all those crucial aspects, and that will give us the correct physical intuition. Then I will tell more about the real-life examples in the next slide. Before that, the second sort of focus of this course will be, of course, a lot of problem-solving and in this case, my goal is to sort of develop a kind of general strategy or a general way of thinking about how to approach any mechanics problem.

So the point is that usually, mechanics is considered a difficult subject, and students often do not know how to approach a problem when the problem is unknown. So if they have seen the problem before they know how to solve it based on some formulas that you may have remembered. But the goal is that, without remembering any formula, how can we think about the problem? The second point is that this course is intended to be for first-year students of various engineering disciplines as well as physics students and other science streams such as chemistry, math, biology, etc. So here I sort of say a few remarks about what I feel is the somewhat difference between approaching mechanics from an engineering point of view and from a physics point of view. So engineering is about control.

So you want to design some machine that you can control to sort of get an output in a controlled way. Whereas the emphasis of physics is on how to find the basic principles or basic equations to analyze the machine, For example, the task of an engineer could be to design a machine and once you make a blueprint, you go ahead and build the machine in real life. Whereas the task of a physicist could be to identify the working principle that explains how the machine works and also to identify the conditions when the design will break down. So the problems that we discuss, so we will try to make a balance between these two aspects so that whatever engineers typically sort of focus on this part of the problem in their various core subject areas will have some idea about these points, which are not usually covered. On the other hand, physics students and other science students should expect that.

so you will get to know somewhat realistic aspects and real-life examples. The text books tend to cover more schematic, idealistic versions of different mechanisms and machines. So we will try to see somewhat more real-life-oriented applications so that you sort of have a better idea about real life. So given these learning objectives, here is the outline for week two. So first, we will sort of introduce a general strategy for solving mechanical problems.



Which we call the system interaction picture for problem solving. So first, we will discuss: What is the system? We will take several examples and in particular, we shall introduce two very common mechanical models: one is point mass and one is rigid body. So these will be kind of repetitively used in various examples so that we can summarize the essential points about them. After that, we will talk about interactions, so we will review our basic concepts about forces, taking examples of common forces in daily life and then we will talk a little bit about the fundamental forces and modern physics point of view about forces. And we will talk about some important aspect of the effect of force on motion.

Then we shall go about reviewing Newton's laws of motion. Now I am sure that all of you have already seen Newton's laws of motion. So my point of view in this course will be that I will assume that you know Newton's laws of motion. So I will sort of tell you how to use or apply Newton's laws to analyze and solve the mechanics problem. So we will keep this particular picture in mind when we review Newton's laws.

Then we shall use Newton's laws to classify the different types of problems. So you see that in mechanics, there can be infinite number of problems and obviously, if you want to develop your skill in solving mechanics problem, The only way to do that is to sort of take a problem, struggle with it, and solve it. But obviously, you have only a finite amount of time; you cannot solve an infinite number of problems. So a smart way is to sort of know: What are the different types of problems? and then sort of know how to approach each type of problem. So this is what we shall do, starting with just using Newton's laws.

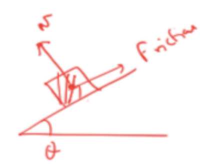
And then we will focus on an important technique for analysis, which is called the free body diagram. So how to draw a free body diagram? we will quickly review it and we shall see that in order to draw free body diagram correctly, you need to keep in mind about three different points about the forces. So how to think about any mechanics problems? So this is our picture. So we will divide the analysis into three different pieces. So the first piece is the system, so you identify the system.

The second piece is interaction; identify the forces and then you do the modeling. Which means you apply the basic physics principle. So you do not have to memorize formulas; instead You just remember the basic physics principles, and then you write down equations. And once you have the equations, you know what are the known quantities given in the problem and What are the unknown quantities you try to solve, those equations? So this is the scheme. So let us see what is meant by the system interaction picture in more detail.

So consider this example of this book on a table. So for example, Imagine this is a table, and I put a book on the table, and we solve it. So the book is at rest on the table. So then the question could be: what is the condition under which the book will be at rest on the table? So what do we mean by system? System is the part that we want to focus on, We want to know the properties of the part whose motion we are interested in studying. For example, in this problem, the system could be our book.

Common forces in everyday life

Fundamental Nature	Common name	Magnitude	Direction	Comment
Gravitational	Weight	$\frac{GMm}{r^2} \equiv mg$ between two point particles of mass m, M at a separation r	Vertically downward along $\hat{r}$	Instant action at a distance.
Electromagnetic (EM)	Contact force	Amonton - Coulomb model	two components normal and tangential *i.e.* friction	
EM	Tension	Uniform but can be non-uniform	along the rope	
EM	Drag force	$F(v) = -\gamma v$ for small v $F(v) = -\gamma v^2$ for big v	$-\vec{v}$ relative	Force depends on velocity. New property: terminal velocity
Generic model	Spring force	$F(x) = -kx$ k spring constant	$\hat{x}$ along extension of spring	Force depends on position. New property: Oscillation



Usually, this is specified clearly in the problem. Sometimes it is not and then we have to sort of use our experience or some thinking to identify the system, but this is usually the easy part. Then everything else that is outside the book is the surrounding. So what are we doing here in this picture? is that this is our entire universe. So this black green blocks represents the entire universe and What we are doing is dividing the entire universe into two pieces.

The first piece is this system, so in this example, this is this book that is our system and then everything else that is outside the book is that part of the universe is called the surrounding. Now why do we break this into these two parts? Because the surrounding and system interact with each other, So in this problem, what could be the surrounding? So in this problem, you can think of the first thing is the let us say this is the table, so the book is in contact with the table. So the table is an important part of the surrounding area. What may be less obvious is that in this problem, the earth is also part of the surrounding Why? Because earth is also interacting with the book, so the earth is pulling the book, The book is filled with a force of gravity due to the earth, which is the weight of the book. So the earth is also part of the surroundings.

So now we sort of describe, like mention, these two very simple mechanical models, Which we will be using in various forms throughout this course. The first model is a point particle or a point mass. So an example could be this famous problem of the motion of the earth. So this is the earth and the earth and this is the sun. So the earth is moving around the sun.

So this is a very famous and one of the earliest mechanics problems; it is called the Kepler problem. So the problem is: what is the path or the orbit that the earth takes to move around the sun? Now, as you know or can easily imagine, In this problem, we represent both the earth and the sun as points. So we ignore that the earth has some size and some particular structure; we just assume it is a point. Similarly, we think about the sun as a point. So this is an extreme simplification of an object, It is usually such a solid object that you ignore its size and internal structure.

Now the point is that you can do that depending on the problem at hand. I mean, the same object can be thought of as a point in one situation but may not be thought of as a point in another situation. So we will see different examples of that kind, so this is just an example of a point particle. So anything can be represented by a point particle. Now what are the types of motion that a point particle can have? So how can it move? So there are three basic types of motion you can easily think of.

One is that it can move in a straight line. So that means that it is moving without changing its velocity. So the arrows here represent the possible direction of velocity of the particle. So assuming this is a particle, it can move in a straight line in one direction. Now if it moves on a plane, let us say in the plane of this book.

The book cover can then move in any direction or along this cover of the plane of the book cover and this direction can be resolved into two independent part. So this is what we have seen in the previous week in the context of vectors. So the velocity is a vector, so it can be resolved into two independent components. So, two directions. Similarly, in three dimensions, let us say in this room that a point particle is moving.

So it is in a straight line and has three independent components. This is what is shown here by these three directions of arrows. These are like cartesian axes; think of them as Cartesian axes. The second way it can move is it can move in a circle. The circle about some external point which is the centre of the circle and you can maybe imagine as an axis, which is going to pass through these slides perpendicular to the slides.

So it is moving around the axis of rotation, so it is moving in a circle. So what is the difference between moving in a straight line and moving in a circle? So in a straight line the when it moves in a straight line the direction of the velocity is constant. Whereas when the direction of the velocity is in the tangent in the direction of the tangent, so it is continuously changing at every point. This is about the direction. What about the magnitude? So the simplest case may be when the magnitude of the velocity is not changing.

So that is possible when it moves along a straight line. It is also possible when it moves along a circle. So the magnitude is not changing, but the direction is continuously changing. The velocity has two fact, two aspect the magnitude and the direction. So the velocity of the particle has a magnitude and a direction given by the unit vector along the direction of velocity.

And you can sort of see that these are kind of independent aspect of velocity You change direction while keeping the magnitude fixed. And then you can think of that there could be a more complex and complicated path along which the particle can move. which is some sort of kind of you can perhaps be thought of as a combination of a straight line movement and a movement in a circle. So this is an example which can be analyzed as kind of a combination of a movement along a straight line and then along a circle. So here I ask a question, and I will leave it for you to think further.

So the question is: can a true point mass, like a point that does not have any size or any structure, exist in real life? So the next example of the system we will be interested in this course are objects, some of which cover some areas of extended objects. In this course, there are objects, some of which cover some areas of extended objects. So their structure and size cannot be ignored. And here are a few examples, so they can be of different types. For example, this is a compact object, then these objects cannot be compact such as the tree in this photo.

so compact, such as this tree in this photo. Then we can give some examples in which there are multiple connected objects. So there are different objects, such as which are connected by various joints and pivots such as the example of human body. For example, if you think of our arm as sort of having a connected piece, Let us say this is one piece, this is another piece, This is perhaps another piece, and they are connected at joints. So the movement of our arm is not a single object at least three different connected pieces joined by some pivots. This is an interesting example, so this is sand art, so this is a sand Taj Mahal.

This is an example of a solid object that is made of small grains of sand. So I put it to sort of show that there is a lot of variety in solid objects, and Rigid does not always mean hard or strong. So why do I mention the word rigid? So this is the second very simple model of a mechanical model that we shall use. So this is for an extended object.

This is for an extended object. A rigid body is an extended object in which the distance between any two points is always fixed. So if I take, let us say, the sphere and take any two points, let us say this is the center, and from the center at any point or from this point to any two points, the distance is always fixed. So if you think about it, it means that the body always moves as a whole. So for example, if I look at this object, So this is a solid object. So this is what you can think of as a rigid object.

So if it moves, everything moves, not just all the points in this paper. Means all the paper weight moves together. So the whole body kind of moves as a single unit. The consequence of that is that if one knows the position of a single point in the body, One knows the position of the whole body.

We shall see in the later part of the course that One often takes a special point inside the body, in our special point, which is called the center of mass.

So this is the second extremely simplified mechanical model. Why do I call it an extremely simplified model? Because in this case, when we represent let us say solid object, We are sort of keeping the information about the size and structure, but we are not allowing any deformation of the object. So because deformation means you are trying to change the distance between two points inside the object, Which is not allowed by the definition of a rigid body. This is why this is an ideal case, any and an ideal model, a very simple model. The moment you include deformation, the analysis of the problem becomes more complicated.

So again, I leave this question for you to think about. So can a true rigid body exist? Can you think of any example of a truly rigid body in real life? So here are some examples of various types of motion of a rigid body. So like before in the case of point mass, it can move along a straight line such as these train moves on the straight railway track. It can also move along a curve. For example, you know that railway track can also be curved at certain places.

Apart from that it can show rotational motion. So this rotational motions we shall see of can be divided into different categories. So this is an example of a mechanism inside a clock. So you can may be call it as a clock pendulum. So this is an example of a fixed axis rotation. So the axis is fixed, this is the pivot point and this is rotating and this wheel is the pivot point for this wheel.

This is rotating around this pivot point. Then we can have some very complicated motion with a rigid body. So you can imagine that possible motion can be more complicated compared to a single point particle. So here is an example. This is called the crank shaft mechanism, slider sliding shaft crank mechanism.

So this is a combination of a translation and rotation. So this kind of mechanism is very common in various such as car, vehicles such as car etc. The one motion that is not possible for a point particle is because it does not have any size. that a point particle cannot rotate about its own axis because it does not have any extension size. This is possible for the case of rigid body. So for example, if you look at this toy, it has a toy with a wheel.

So this wheel can rotate about an axis, which is represented by the axle of the wheel. So this rod, which is the axle of the wheel, can rotate about itself. A rigid body can rotate about an axis passing through itself. So that means that When a rigid body moves in general, its motion is always a combination of translation and rotation. So this aspect will be discussed in more detail in the later part of the course.

After that this introduction to some, so now we have some example and ideas about systems and I have seen two mechanical ideal cases of systems that we will consider. Let us review the common forces in everyday life. So here is a table in which the second column represents some common forces and the common names of the forces. So first is the third column, and the fourth column gives you the magnitude and direction of the forces. The first column will come into the next slide and at the moment, the last column is a comment.

Which you may ignore at the moment. So the first point to mention is that the first very important force is weight. The gravitational attraction of the earth that we all have on living on earth always feels this force. So our everyday experience, our physical intuition about day-to-day lives or Our surroundings are heavily biased by this force; we always feel it. And as you know, the magnitude is given by the mass of an object times the strength of the gravitational field at the location of the object given by small g, and you can calculate small g using Newton's formula for universal gravitation and this force is directed towards the centre of the earth, which is on the surface of earth. means that is vertically downward along the any radius towards the centre.

The second very important force that heavily biased our physical intuition and everyday experience is friction. So here is a common example of friction. So we as a human being we are immersed in a atmosphere of a fluid the air. So when we move, and sometimes we are also immersed in the water, we swim or go somewhere by boat or something. So we feel this friction in air and water; these are called drag forces.

So we will come to that in more detail in the later part of this course. So friction is another very important common force. Then, if you think about mechanical force, usually we think about a pushing force or pulling force or tension force, something that is generally called the contact force. And so the prototype example will perhaps be a block-on-a plane problem. So this is a block which is on an inclined plane with an angle theta and then there is a force of interaction between the block and the plane and this in general has two, so this is an inter-dimensional.

And then finally, We have a model called spring force. So this is again a very useful force, both for engineering applications. So spring is extremely useful, not only because of the mechanical springs that we can use to build various mechanical part of a mechanism, but also it has a exact analogy in electrical circuit. So in terms of the components of capacitors and resistors, and so on. So this is a very useful point for practical application. In physics, it is also very, very important force because this is one of the most simple force that we can often use in a complicated situation.

We sort of make progress if we assume that the interaction forces are like a spring force. Which is given by this simple formula. F = -k x, where x is the extension of the spring. Now I must mention that from a modern 21st-century physics point of view. So for all these different forces, there are only four different fundamental interactions.

Fundamental interactions

- Strong nuclear force
- Weak nuclear force
- Electromagnetic force
- Gravity

$$F_e = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r^2} \sim 10^{-28} N$$

$$F_G = G\frac{m^2}{r^2} \sim 10^{-70} N$$

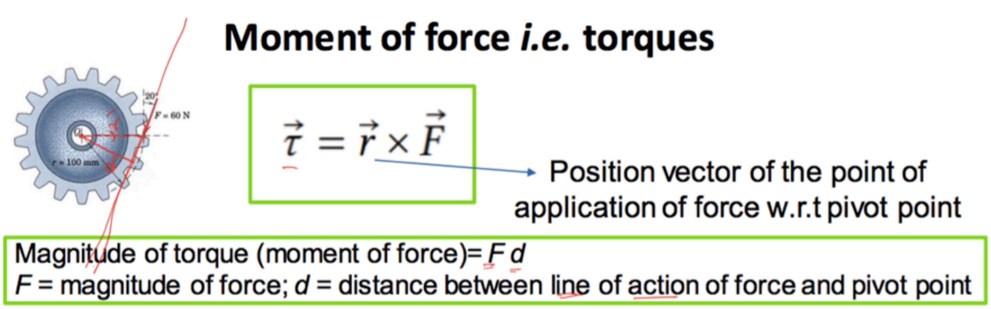
Electromagnetic vs. gravitational force between two electrons at rest

So the strong nuclear force, the weak nuclear force, the electromagnetic force, and gravity Now the strong and weak forces exist only within a nucleus. So outside nucleus anything that is atomic size onwards, so all the forces are either electric force, electromagnetic force, or gravity. So gravity is, in our list, basically the fundamental origin. For all these forces, except the weight of an object basically coming from the electromagnetic interactions Due to the electrical charges and electrical currents, this is a very fundamental picture. We shall not go into very much detail about this in this course but The engineering students should keep this in mind as the fundamental picture.

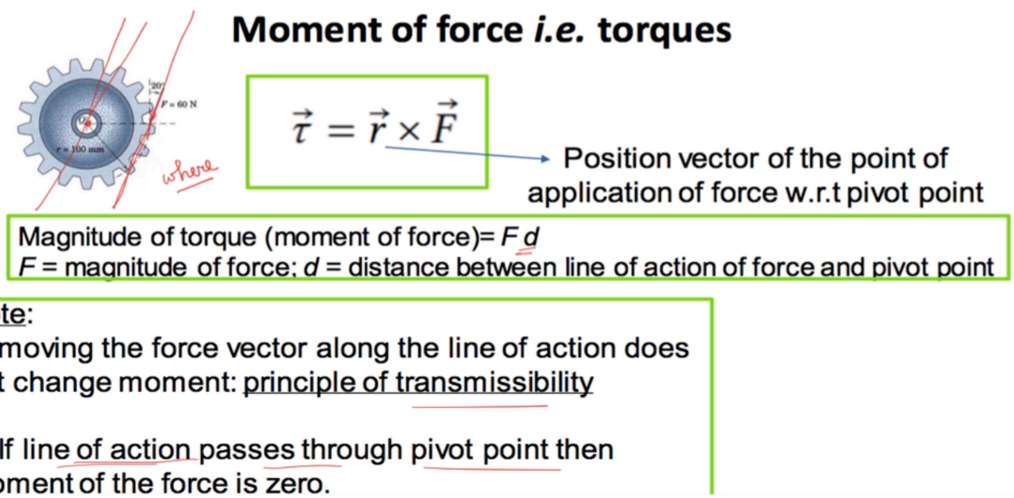
The electromagnetic force is usually extremely strong compared to the gravitational force. For example, here I show calculate the electromagnetic force between two electrons at rest so at certain distance r, what is the value of the electromagnetic force? the coulomb force is obviously very small but the value of the gravitational force between two electrons at the same distance is extremely small compared to the electromagnetic force. So that is why, in day-to-day situations, we only use gravitational force. We need to consider gravitational force, When one of the object is the earth, that is gravitation due to the earth, or you need to have a mass of the scale of the size of earth to really consider the electromagnetic interaction.

Another point that I will quickly mention is that before going to Newton's law. What are the effects of forces? So we shall see in the next lecture The forces cause acceleration, so this is Newton's law. So basically, it means that For example, if I take this book and apply some forces to push it, it will start to move. Now there are two types of motion possible: one is translation, which means it starts moving in a straight line, and the other is rotation. This is sometimes a little bit counterintuitive, but the effect of force can also cause an object to rotate and so this is a very simple way to understand this. For example, if I take this book in this position and sort of take it as a hinge, Imagine that this is like a door and if I apply some force, you can see that it will start to rotate about this backbone of the book.

The point is to analyze the rotational aspect of the force you know in the previous so force is a vector so it has a magnitude and direction. In addition to magnitude and direction, we need to know the line of action of the force. It is also equally necessary to analyze this effect of rotation. So that is why We need this quantity called torque, or the moment of force. So I just quickly defined What is torque? The torque is, as you know, defined by this relation, so for example, you consider this gear wheel, so there is a force applied on the edge of the wheel in a certain direction as represented by this red arrow, and O is the pivot point about which the wheel is rotating.



So the point R represents the position vector of the point of application of the wheel and then the torque is defined by this cross product between the R and the force F and if you apply the formula for cross product, you will turn out that the magnitude of the torque is given by the magnitude of the force times the distance between the line of action so this is called a line of action. So if you extend the direction of the force on both side this gives you the line of action so the line of action of the force and the distance mean the perpendicular distance so if you drop a perpendicular from the pivot point O to the line of action, This represents D, so that gives you D, so that D is multiplied by force. So the point is that The rotational effect depends not only on F but also on this distance, D. Now there are two remarks. The first is that if you move, this is the line of action if you move this force, without changing its magnitude and direction along this line of action, It does not change the torque.



This is called the principle of transmissibility. The second is that if the line of action passes through the pivot point, then the moment of the force, which is the torque, is 0. So why? because if line of action passes through the same force if it passes through this point through O, then the distance from O that is D is 0. Hence, the torque is 0. So that means you will not be able to rotate, or whether you can rotate this gear wheel depends not only on the magnitude and direction of the force but also on the line of action where you are applying the force. So in the next lecture, we shall review Newton's law.

Thank you.